Energy Economics 69 (2018) 111–127

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneco

Energy consumption and CO_2 emissions convergence in European Union member countries. A tonneau des Danaides?

Konstantinos Elias Kounetas

Department of Economics, University of Patras, Patras, Rio 26504, Greece

ARTICLE INFO

Article history:
Received 16 January 2017
Received in revised form 8 October 2017
Accepted 23 November 2017
Available online 2 December 2017

JEL classification:
Q4
Q5
C2
O47
C69
O5

Keywords:
European countries
Convergence
Energy consumption
Carbonization index
GHGs

ABSTRACT

As the consumption of energy is responsible for approximately, 80% of GHG in EU (IEA, 2008), the impact of energy activity on the environment has received increasing attention over the last decades from scholars, researchers, politicians and society as a whole. Within EU member countries it is commonly accepted that the design of energy and mitigation policies either at national or at European level require a detailed and integrated investigation of convergence-divergence pattern among the participating countries. In this paper, we examine the distribution dynamics of energy consumption and CO_2 emissions, their intensities as well as the carbonization index in 23 European countries over a forty one year period, in particular from 1970 to 2010. For this purpose we used Quah's methodology which is based on the dynamics of cross-section distributions. The main conclusion is that for all the examined variables the hypothesis of convergence patterns for the EU sample is not valid. Moreover, regarding each examined variable different groups of polarization established. Important differences occur across EU countries according to the climate type with respect to the examined variables. Our analysis provides strong evidence supporting the fact that national and European energy and mitigation policies should be implemented according to the non-convergence paradigm. The body of evidence provided by our analysis is of great importance to energy policy makers and for issues related to climate change.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction and motivation

The Intergovernmental Panel on Climate Change has stated that the most significant environmental problem over the last 50 years is that of global warming due to anthropogenic greenhouse gas emissions (IPCC Climate Change, 2007). Emissions released in the atmosphere are highly correlated with energy consumption (Soytas and Sari, 2009; IEA, 2008). A solution to global warming entails reducing such emissions and increasing energy efficiency. The significance of these policies was highlighted by the signing of the Kyoto Agreement in 1997 and subsequent efforts in Copenhagen, (2010), Durban (2011), Warsaw (2013) and in Paris (2015) which helped accomplish an international agreement towards reducing greenhouse gas emissions.

Factors including the repercussions of climate change, the scarcity of fossil fuels exacerbated by low efficiency and wastage, increasing energy dependency and security (Costantini et al., 2007), high volatility of energy prices (Regnier, 2007), carbon pricing (Jenkins, 2014) as well as indigenous energy production capacity compelled the European Union to devote a large portion of its available resources towards designing and implementing mitigation policies so as to achieve a better level of sustainable development (Commission Directive 2012/27/EU, European Commission, 2007; European Commission, 2013; IEA, 2000) and thereby on the other hand reducing energy consumption and on the other improving energy efficiency (2012/27/EU;2009/125/EC;2010/30/EU). In this line, the European Parliament with the decision (No. 409/2009/CE) put a final end for the realization of 2020 agenda fulfillment, laying the foundation for achieving the objectives of 2050 agenda.

Although the European Union pressured their member countries towards implementing energy and carbon reducing policies, through an "umbrella" of common policies, the situation of the current European countries members is quite different. Differences in income and GDP (North-South division), production and energy structure, level of energy saving and efficiency as well as emissions per capita reveal a rather inhomogeneous picture in relation to energy and environmental variables and components. Thus, having good knowledge of the concepts of energy, emissions and other characteristics with respect to the convergence-divergence patterns and their evolution in EU member countries is essential for better policy design as well as cost minimization. For instance, it would be easier to establish different policies and subsequent targets knowing that energy consumption or emissions intensity congregate in one point instead of more.

https://doi.org/10.1016/j.eneco.2017.11.015
0140-9883/© 2017 Elsevier B.V. All rights reserved.

In this work, we distinguish between energy consumption and intensity, CO_2 emissions and its intensity and carbonization index examining the convergence-divergence hypothesis for a European countries sample over the 1970–2010 period. The investigation of convergence hypothesis can provide policy makers, governments, authorities and researchers with new insights concerning the decision of EU environmental and energy policies (Padilla and Duro, 2011). Moreover, it can operate additionally with similar studies at a national and industrial level revealing the polarization or not with respect to the examined variables.

On the other hand, the objective of this study is to contribute new intuition to the energy-emission convergence literature by examining a phenomenologically homogeneous sample of countries (in terms of common agreements, Annex II countries, common regulations, etc). The results of this research aim to provide some insight into relevant issues such as whether European countries share convergence or divergence patterns concerning energy intensity, consumption and emissions released in the atmosphere. In our point of view, identifying whether such patterns exist or not, could be a matter of interest for policymakers and governments in order to schedule and design more focused and effective environmental and energy policies and measures. Although there are several individual studies on energy and emissions variables that deserve merit, no previous study has yet examined all the above-mentioned characteristics with a complete and integrated picture at a European level.

Convergence is a basic empirical issue and its analysis has stimulated a wide-ranging and rather heated debate. Different methods, drawn from the literature on economic growth, have been employed to determine convergence, classified in three broad threads of analysis. Within the first thread-time series approach, a variety of methods has been adopted, among others, including pairwise convergence approach (Pesaran, 2007) and stochastic convergence (Carlino and Mills, 1993). The second thread refers to the well-known concepts of β and σ-convergence typified by the seminal papers by Barro and Sala-i-Martin (1992) and Mankiw et al. (1992) while the third one adopts distribution dynamics that put the emphasis on the intra-distributional mobility characterizing sequences of cross-sectional distributions over time. First Quah, (1993, 1996) and later on Durlauf et al. (2005) emphasize on the inadequacies of the regression approach in comparison with the distribution dynamics approach using theoretical arguments. They argue that regression approaches are unable to reveal the dynamics of the entire cross-sectional distribution and thus, their findings might be misleading. According to Quah (1993) distributional dynamics approach, stochastic kernel describes the law of motion of a sequence of distribution and it serves to retrieve the evolution of the probability distribution of a random variable (usually GDP) along time allowing it to overcome the limitations of conventional convergence analysis focus on the dynamic properties of the series. Distribution dynamics approach (Quah, 1996, 1997) resulted in the literature from the necessity to substitute discrete transition matrices. In this way, stochastic kernels can be achieved by estimating the density function of a distribution over a given period, lets say $t+k$, conditioned on the values corresponding to a previous period, t. Moreover, stochastic kernel density allows the estimation of a transition function using all the information of the data from the initial period to the last and the transition process avoiding the problem of dynamics distortion through the discretization (Andrade et al., 2004). In other words, a stochastic kernel represents the density of a random variable at one point of time into the density in a subsequent period and thus, can be thought as a set of conditional densities.

The remaining paper is organized as follows. Section 2 discuss analogous studies while Section 3 presents the methodology adopted. Section 4 provides a discussion of the data used and Section 5 is devoted to presenting and discussing the results. Finally, Section 6 concludes.

2. Review of the literature

Global warming and climate change has been considered as the most important on-going problem over the last few decades. The United Nations, the European Union, governments of many countries and worldwide independent organizations have been attempting to propose policies and measures to reduce the negative impact of climate change effects examining different countries' behaviors (Costantini et al., 2017). Policies incentivizing such technological innovation and related cost reductions may also have an important effect on countries' energy and environmental behavior (Reichardt and Rogge, 2016; Hoppmann et al., 2013). In the existing literature, a plethora of studies has concentrated on the question of GDP per capita or income convergence but much less on the question of energy consumption and carbon emissions convergence or divergence. Moreover, a sufficient number has focused on individual measures using different methodological approaches, dataset and time periods. To date, there are many studies using stationarity and panel unit root tests while a limited number focuses on Quah's methodology.

Convergence as an ambiguous concept with many interpretations is based on the assumption that different units are initially in a state of disequilibrium. In particular, economic growth literature makes extensive use of the concept of β and σ convergence with several studies (i.e Quah, 1993, 1996, 1997; Magrini, 1999, 2004) following the seminal work of Baumol (1986) and Barro and Sala-i-Martin (1991, 1992). Previous studies concerning convergence issues cover variables such as per capita personal income (Barro and Sala-i-Martin, 1991), cross country income distribution (Quah, 1993, 1997; Johnson, 2000) and GDP per capita (Durlauf and Quah, 1999; Bulli, 2001; Andrade et al., 2004). The relevant literature considers three different types of convergence: β-convergence, σ-convergence and distributional dynamics. Note should be made that distributional dynamics approach started being applied to other fields rather than energy and environmental economics.

However, in a series of papers Quah, (1993, 1996; 1997) and later Durlauf et al. (2005) has persuasively criticized standard regression approaches to studying convergence issues of mobility, stratification and polarization. They argue on the facts that the steady state to which countries are converging is not the single stable steady state of neoclassical theory and it is independent of the initial conditions providing misleading results. Moreover, the specific approaches completely ignore that various countries may modify their relative position over time and for cases of overtaking, β-convergence, σ-convergence can lead us to conclude erroneously in favor of convergence since these approaches focus on the average rather than the dynamics of the entire distribution (Johnson, 2005).

Initially, turning our attention to energy consumption and energy intensity we quote that the literature provides studies, using alternative methodological approaches, on how countries at different stages of development behave on this issue aiming mainly on energy intensity. Nielsson (1993) and Goldemberg (1996) for a dataset of industrialized countries found a type of convergence to a common club while Mielnik and Goldemberg (2000) examining 41 countries over 1971–1992 revealed a decreasing trajectory for 18 developed countries and a decreasing one for developing.

In turn, Ezcurra (2007a,b) and Markandya et al. (2006) using the convergence methodology showed that for a dataset consisting of several transition countries, a mode of converging to the European average level exists. Expanding on previous studies and number of investigated individuals Liddle (2010) using two samples with different number and kind of participated countries as well as a

different time span presented a pattern of convergence, in particular convergence for different regions. Contrary to this, Le Pen and Sévi (2010) using a convergence test method developed by Pesaran (2007) for 97 countries during the 1971–2004 period suggest a diverging pattern for the whole sample but with an individual regional convergence clubs creation.[1]

The empirical evidence of CO_2 emissions convergence-divergence hypothesis reveal contradictory results. On the one hand, we have several studies that support the idea of convergence while other studies seems to reject the specific hypothesis. For example, Strazicich and List (2003), using panel unit root tests and cross-sectional regressions, examining 21 OECD countries over the 1960–1997 period found evidence of CO_2 emissions convergence. Similarly, Westerlund and Basher (2008) found a strong support for CO_2 emissions convergence for 16 developed countries that covers the period from 1870 to 2002 while Herrerias (2012) results support the same idea across 25 European countries over the 1920–2007 period. In addition, Romero-Ávila (2008) provide strong evidence for stochastic and deterministic convergence for 23 countries over the period 1960-2002 with Jobert et al. (2010), using a Bayesian estimation to conclude the same. In the same line, Nguyen Van (2005) and Stegman (2005) showed evidence for a convergence path for industrialized countries but not for the whole sample.

In contrast, Aldy (2006) presents no evidence of CO_2 emissions per capita convergence for a global sample of 88 countries during the 1960–2000 period while Nguyen Van (2005) suggests the same for a sample of 100 industrialized countries but also reports convergence. In the rejection of convergence hypothesis concludes Barassi et al. (2008) examining OECD countries for 1950–2002 and Lee and Chang (2008) while Ezcurra (2007a,b) analyze the spatial distribution of 87 countries the period 1960–1999 with a significant evidence of increasing disparities over time and Stegman (2005) supports the evidence of convergence distinction between industrialized and not countries. Finally, according to Camarero et al. (2013) four different groups that converge to different equilibrium have been revealed for the creation of CO_2 emissions over GDP and energy consumption *(the so-called carbonization index)*.

3. Methodology

3.1. The regression approach

The regression approach[2] has its theoretical foundation in the traditional neoclassical model of growth originally set out by Solow (1956, 1957). The key parameter to be empirically tested is the rate at which the representative economy approaches its steady state growth path denoted as β-convergence[3]. We test for unconditional β-convergence by using the following equation:

$$y_{it} = a_i + (1-\beta_i)y_{i0} + u_i \tag{1}$$

where y_{it} denote the logarithm of the variables of interest, in country i and period t. The measure of β-convergence is then derived from the OLS regression of y_{it} on a constant and y_{i0} where 0 is the first period of investigation. The estimate of β_i indicates the rate of β-convergence while the so-called "half life" is calculated by using the ratio $\frac{log2}{\beta_i}$.

However, some authors have criticized the use of β-convergence emphasizing the analogy between regressions of growth rates over initial levels and Galton's fallacy (Quah, 1993) of regression towards the mean. A solution to this problem was the introduction of σ-convergence measuring the change in the value of the standard deviation from period 0 to period T $(\hat{\sigma_{iT}} - \hat{\sigma_{i0}})$. The extent of the statistical significance of this measure under the null hypothesis of no σ-convergence is computed as follows (Carree and Klomp, 1997):

$$\sigma_{it} = \sqrt{N}\frac{\frac{\hat{\sigma}_{i0}^2}{(\hat{\sigma}_{it}^2-1)}}{2\sqrt{1-\left(1-\hat{\beta}_{it}\right)}} \tag{2}$$

3.2. Distribution dynamics approach

This study uses distributional dynamics that adopts a Markov chain as one of the alternatives comparing with β and σ-convergence. The non-parametric modeling allows us to study the dynamics of the entire distribution of the variables of interest and not an average behavior as is in most of time series studies. Furthermore, one of the most significant features refers to the fact that equilibrium is stochastic and not deterministic as is in the previous approaches. Thus, state probabilities are considered fixed and countries can freely move among the states according to the transition probability matrix. In advance, the specific approach embodies notions of increasing returns associated with endogenous growth theory (Quah, 1996) while allow us to consider neoclassical assumptions in a more liberal way. Finally, distributional dynamics approach is seen to accord with the real world where countries move between energy and environmental levels under the presence of shocks (Fingleton, 1999) and it is suitable when the analysis is limited to a "homogeneous" set of economies (Barro and Sala-i-Martin, 1991, 1992) allowing for heterogeneity across them (Bimonte, 2009).

Let us now call the value of interest defined as a Markovian stochastic process $X_i^j(t) : t > 0$ where j is the value of variables of interest (i.e. energy consumption) for the i country at time t[4]. Then denote by $F_x^j(t)$ the distribution of $X_i^j(t) : t > 0$ and by $F_x^j(t)$ a probability measure associated to $F_x^j(t)$.

We can consider $\forall A \subseteq E \subseteq R^5$ a law of motion (Magrini, 2004;) that can be written as the convolution

$$f_x^i(t+s) = M_{t,s} f_x^j(t) \tag{3}$$

where $M_{t,s}$ is a stochastic kernel[6] (Meyn and Tweedie, 1997) that maps the density at time t to $t+s$ and tracks where point if $f_x(t)$ ends up to $f_x(t+s)$[7]. Following strictly Quah (1997), we can assume that

$$f_x(t+s) = \int M_{t,s}(X,A) f_x(x)dx \tag{4}$$

[1] Studies that examine the development of energy intensity over time and its relationship with the sectoral economic development has been conducted by Miketa and Mulder (2005) and Mulder and De Groot (2007).

[2] We owe this to an anonymous referee

[3] See Barro and Sala-i-Martin (1992) for a detailed description of regression approach main features

[4] For reasons of simplicity, we will $X_i(t) : t > 0$.

[5] Where E is the state space of X.

[6] Satisfying the Markovian and homogeneity properties.

[7] Taking into account that the process is Markov then we can assume that $\forall t, s M_t + s = M_t M_s$ and with iterations of Eq. (1) the predictors of future cross-sectional distributions will follow that $f_x(m(t+s) = M_s^m f_x(t)$.

which, under certain conditions to be satisfied, implies that

$$f_t + s(y) = \int_E f_s(y/x) f_t(x) dx \tag{5}$$

where $f_s(y/x)$ and $f_s(y/x)$ are the density functions of $M_{t,s}(X,A)$ and $F_x^j(t)$ respectively.

The joint density function at moments t and $t+s$ is estimated by the Gaussian kernel method (Fotopoulos, 2006) divided by the implicit marginal distribution at t in order to obtain the corresponding probabilities as following:

$$\hat{f}(y/x) = \frac{\hat{f}(y,x)}{\hat{f}(x)}. \tag{6}$$

Finally, the long run density can be estimated as the solution of

$$f_\infty(y) = \int_{-\infty}^{+\infty} f_y(y/x) f_\infty(x) dx \tag{7}$$

(Johnson, 2000, 2005).

The difficulty with distributional dynamics analysis is that while the Markov analysis allows us to identify convergence clubs; we can't determine the countries that formed each club. Moreover, other disadvantages associated with the Markov approach include the rather vague association with economic theory and the problem of spatial dependence and inference (Fingleton, 1999; Fingleton and McCombie, 1998). Finally, significant changes from past experience in policies or technologies may not be well represented by this approach (Aldy, 2006)[8].

4. Data and variables

Having reviewed the literature on energy consumption and emissions convergence, we shift the focus describing the data used in our analysis. The data used to examine possible divergence or convergence patterns for EU countries basically consist of data on CO_2 emissions and energy consumption. Concerning CO_2 emissions variable we are aware that are presented in line with UNFCCC accounting rules and IPCC reporting guidelines, which don't often readily capture changes in fuel and the sectoral mix of energy use both upstream (e.g. emissions associated with the combustion of fossil fuels in electricity production that is subsequently used by consumers) and downstream (e.g. combustion of fossil fuels such as natural gas and coal). Thus, for the CO_2 emissions variable we have used emissions linked with energy combustion expressed in metric tons. Moreover, regarding the energy consumption variable we used total primary energy supply (TPES), in units of tons of oil equivalent per thousand year-2000 purchasing price parity (PPP) US dollars (USD) from International Energy Agency's (IEA, 2000) data series. Total primary energy supply (TPES) accounts for all energy consumed within a country (Liddle, 2010) and is made up of production imports excluding exports, international marine bunkers and international aviation bunkers. Total primary energy supply adjusts for the energy consumed in producing electricity and it is different from the delivered energy (Liddle, 2010; Jakob et al., 2012)[9].

In addition and taking into account a more integrated analysis, energy consumption and CO_2 emissions per GDP forming two additional variables (energy and CO_2 emissions intensity) were used as alternative variables. Finally, to test the existence for convergence clubs we also used the so-called carbonization index defined as the ratio of CO_2 emissions over energy consumption.

As has been referred, we have composed a dataset derived from two distinct and reliable data sources. More specifically, data on the energy use was collected through the International Energy Agency database while data on CO_2 emissions was collected from Enerdata. This resulted in a balanced panel consisting of eighteen European countries over a forty one years period from 1970 to 2010. This dataset provides the opportunity to study any convergence or divergence behavior of these countries. Table 1 provides the descriptive statistics by country and examined variable from 1970 to 2010.

In order to get a feeling of the convergence process concerning our variables of interest, we begin with a graphical inspection of the data for the EU countries. To foreshadow, the more formal treatment in the next section, Fig. 1 plots the log of energy consumption, CO_2 emissions and the value of carbonization index during the period of examination. From there, it is possible to observe the heterogeneous behavior of UK, France, Germany, Italy and Poland concerning energy consumption comparing the remaining countries. It seems that, approximately, the last ten years this behavior remains stable and decreasing for the majority of the observed countries. On the other hand, in terms of CO_2 emissions, the same picture reveals the existence of different country emitter clubs but this gradual decrease to have tested for two decades. We also picture a similar behavior for the carbonization index but we can observe the decreasing, after 1996, behavior of Germany and Poland and the increasing one for Spain, Italy, France and Poland.

We also investigate the behavior of EU countries concerning energy and CO_2 emission intensity using a graphical representation. Fig. 2 shows the evolution of the two above-mentioned variables over the period examined respectively. The figure clearly illustrates the idiosyncratic behavior of Luxembourg and Finland and the creation of a rather homogeneous club of the remaining countries. However, there is a strong tendency for countries to move together for both intensities but with a different trend. Concerning energy intensity there is a slightly increasing trend while the opposite one holds for CO_2 intensity case.

5. Results and discussion

5.1. Empirical results for the regression approach

We begin our discussion turning to the analysis of β-convergence by looking at Table 1 in which the estimate of Eq. (1) using ordinary least squares is reported for each of our variables. The estimation results indicate the existence of a process of unconditional convergence across EU countries for all of our variables. In particular for energy consumption, the estimated value of the rate of convergence towards the common steady state is 2.613% and statistically significant. The time needed to halve the gap between initial and steady state level is equal to 42.179 periods. Analogous interpretations can be derived from the estimates of β-convergence for the remaining variables of interest.

However, in the literature it is well-known that β-convergence is not a necessary (Furceri, 2005), but not a sufficient condition for the reduction in the dispersion of our variables of interest (σ-convergence). Table 2 reports the standard deviation and the coefficient of the two series for each variable respectively. To formally test the null hypothesis of equal variances the table also reports the t-test proposed by Carree and Klomp (1997). As it can be seen the statistic indicate the statistically significant variance

[8] We would like to thank an anonymous referee for highlighting this issue.
[9] We would like to thank two anonymous referees for their recommendation.

decrease. In other word we found unambiguous evidence in favor of both unconditional β and σ convergence for energy consumption. Analogous conclusions can be derived for the remaining variables. Based on our results a researcher following this stream of literature would probably conclude that with respect to energy consumption, CO_2 emissions, carbonization index, energy intensity and CO_2 intensity the EU countries are unconditionally converging at average rates of 2.13%, 1.84%, 1.98%, 2.25% and 1.85% respectively. Moreover, the cross-sectional dispersion is decreasing significantly.

5.2. Empirical results for the distribution dynamics approach

We begin the presentation of results focusing on energy consumption. The stochastic Kernel in Fig. 1 shows how the cross sectoral energy consumption in 1970 evolves into 2010. Thus, over the 41-year a three peaks property manifests. Each specific peak reflects a comparatively large number of observed transitions from a particular part of the distribution to another while having a constant point in x-axis. We can understand the estimated distribution of energy consumption in 2010 at its initial level 1970. A large portion of the probability mass is concentrated along the 45° diagonal while the existence of 3 peaks along the diagonal indicates the presence of individual convergence clubs. More specifically there are two local maxima in both low and high energy intensity parts and a third one in the middle part of relative energy intensity.

Turning our attention to the corresponding contour plot in Fig. 2 we notice that during the examined period, European countries have a low probability of changing their relative position in one year in terms of energy consumption tending to remain where there have been. Moreover, the contour plot for energy consumption reveals a significant mass portion along the diagonal suggesting that the mobility is low.

A possible explanation can be attributed to the different structures of the economies participating in our sample. It is well known that the different level of a country's consumption can be regarded as a characteristic depicting their different economic structure. Therefore, countries that appear to be more or less developed can broadly converge to similar patterns of energy consumption (Jakob et al., 2012; Camarero et al., 2013). This explanation is consistent with the hypothesis that growth in EU countries appears to be decoupled, partially, from energy consumption and therefore the two additional factors of efficient energy use (Camarero et al., 2013) and fuel mix (Liddle, 2009) are of great importance.

The probabilities for energy intensity, this time, of a transition from one part of European countries distribution to another periodically over a time-horizon 1970–2010 is depicted in Fig. 3. The difference with the energy consumption variable is the existence of two peaks and the absence of the lower part. Thus, the specific finding compared with the former regarding energy consumption provides some evidence for an enhanced decoupling of energy consumption. Fig. 4 reveals that in terms of energy intensity the probability mass is basically concentrated around the main diagonal indicating the limited degree of mobility and persistence. There are also two local maxima in both high and middle energy intensity with a shallower low part.

This specific result supports the concept that there is no convergence mass for European countries thereby suggesting the formation of two main clubs and further denoting the absence of the lower in energy intensity terms part. Moreover it appears to challenge the work of Jobert et al. (2010) and Marrero (2010) who found significant evidence of convergence for European countries.

The two peaks phenomenon for energy intensity that directly links energy consumption and economic activity could be further explained in terms of factor accumulation deformations, factor prices changes that acts as inducement for the introduction of new technologies (Binswanger et al., 1978) and localized technological change (Antonelli, 2006; Mulder and De Groot, 2012). Factor accumulation distortions (Easterly and Levine, 2001) of the examined European countries in both physical and in terms of human capital maybe important to facilitate the objective of two clubs creation. For instance, physical capital investment may embody new energy saving technologies to help in catching up the frontier but this is not the case for all the countries.

Furthermore, although with varying rates of embodiment, environmental and energy related technologies have been adopted creating, relatively successful, at least in the reduction of emissions and energy consumption reduction, serious problems still remain. Various factors responsible for the differences between energy intensities between EU countries include the irreversible nature of the above-mentioned investments, localized and limited knowledge, issues concerning information asymmetries as well as the existence of a large number of barriers. From a global perspective, heterogeneity in production and factor markets as well as rivalry of interdependent product markets facilitates bias in technological change. According to Liddle (2009), additional factors affecting country's energy intensity convergence behavior include its fuel mix, its economic structure, its sectoral composition as well as its level of energy efficiency.

The Epanechnikov Kernel regarding the CO_2 emissions case has been used by estimating the joint density of dividing it by the implied marginal distribution. A three peaks is again maintained. Our finding therefore contradicts several studies which found convergence paths and climate models whose projections support convergence (Stegman, 2005). An initial explanation for the specific variable arises from the inequality that still exists on GDP per capita (Padilla and Duro, 2011) and the uneven distribution of fossil fuels (Barassi et al., 2008). More precisely, our finding highlights the fact that merely shifting the energy mix to renewable sources could yield reductions in anthropogenic greenhouse gas emission.

On the other hand, the analogous stochastic kernel for the conditioned variable of CO_2 emissions intensity reveals the existence of four specific clubs. By giving attention to the contour plot, the fact that a large portion of the above-mentioned variables probability mass remains clustered around the main diagonal indicates that most of the European countries in 2010 had the same relative CO_2 emissions and intensity they had in 1970. The fact that the probability mass of the examined variable is concentrated in the main diagonal does not support the idea that European countries situated at both ends of the relative distribution exchanged their relative position over the 1970–2011 period. In other words, most countries occupied the same positions in 2010 as they did in 1970.

The presence of CO_2 emissions inequalities among European countries encouraged a discussion on the role of technological change, climate conditions, economic performance, type of regulations and competitiveness level. While the major factor explaining divergence exists on GDP per capita (Padilla and Duro, 2013) and the fact that European countries appear with completely different climatological conditions (Ezcurra, 2007a,b; Nordhaus, 2007) crucial seems to be the effect of harmonization that strength convergence (Vogel, 1995), the compliance of international agreements obligations and the derived type of regulations imposed and implemented.

Finally, the conditional density of the carbonization index presented in Fig. 7 has three distinctive peaks denoting the formation of three distinctive groups of economies. Each peak is considered as coalitions of economies or groups. Low mobility and high persistence have again been observed since the mass of the contour plot is concentrated along the 45° diagonal. The carbonization index data moreover exhibits the tallest peak in the center of the distribution implying a tendency for countries to congregate here. The specific result corroborates the idea of no convergence and the formation of individual clubs.

The formation of the clubs is highly correlated with the fact that final energy consumption breaks down by primal energy sources (Camarero et al., 2013; Padilla and Duro, 2013). Thus, energy mix, depending on policy choices, the extent of the availability of energy sources as well as the type of energy needs, is of great importance. The inequalities in energy sources can easily be detected in EU countries since many make use of different shares. For example, while Germany has a share of 26.2 on renewables and almost 26 on lignite, France appears with a high percentage on nuclear power. Italy, in addition, has a share 44 of gas and countries such as Poland, Czech Republic and Greece have a significant share on coal[10]

The corresponding ergodic distribution was estimated by iteration of the stochastic kernel to reach the convergence of the process for all the above-mentioned variables. Fig. 8 presents the estimations for the examined variables. The sequence of the ergodic distributions shows that the bimodal (i.e twin peaked) feature of the distribution is becoming more pronounced comparing the two different cohorts. While in terms of nominal values of energy consumption and CO_2 emissions there is a long run prediction for the creation of one club, in the case of corresponding intensities a two peak pattern reveals. The specific finding does not complement the previous regarding energy consumption per capita, CO_2 per capita and carbonization index, thereby indicating that there have been serious improvements that, in future, will lead to a unimodal distribution. Taking into account the economic dimension of energy and CO_2 emissions more effort is required by the European countries members to prevent climate change and achieve energy dependency.

5.3. The climate dimension

Up to this point, we have examined the evolution of the spatial distribution of our variables of interest for the period 1970-2010. However, our analysis gives no insight into the explanatory factors of the observed variables levels due to methodological reasons[11]. Thus, given this inadequacy, it will be interesting to examine the role played by different variables in this context using the examination of additional factors dividing our sample into subgroups. Subdividing Eu countries with the help of climate criteria may lead to different results (Del Río González, 2009). However, the examination of subgroups sets as a necessary rule to ensure the performance of the proposed model in terms of size and time dimension.

To study the existence of convergence among different country groups we perform the distribution dynamic analysis according to the climate classification developed by the Köppen-Geiger climate type (Peel et al., 2007). Following Köppen-Geiger climate type we divide EU countries in two categories ensuring the possibility of having robust results. The two categories contain countries belonging to temperate and cold climate type following the broader categorization of Köppen-Geiger criteria[12].

The main difference examining the two groups with what we have seen before concerns the different club formation according to energy and CO_2 emissions intensities and CO_2 emission releases[13]. Let us now look at the empirical results about convergence, starting from CO_2 emission releases. According to the stochastic kernels and contour plots depicted in Fig. 11 it seems that the polarization phenomena exist for both two groups. However, as it can be seen countries that have cold climate present to have three distinctive peaks. On the other hand, for the temperate climate countries two major peaks revealed.

Regarding CO_2 emissions intensity polarization phenomena are still detectable from Fig. 12 for both groups. Although we can deduce the existence of two major peaks for the countries with temperate and cold climate type the picture is completely different comparing with the whole sample. Shifting our attention to energy intensity the estimates of the stochastic kernel and the contour plot depicted in Fig. 13 shows the existence of three local maxima for the cold climate countries group and two local maxima and of sizeable deep in the middle for the temperate group.

Finally, the corresponding ergodic distributions for the two subgroups are reported in Fig. 14. As we can observe both groups follow the same behavior comparing with the entire sample for CO_2 emission variable. However, the probability mass for the cold climate and temperate group countries is around 1.5 and 2.1 respectively. Differences can also be observed for CO_2 emission and energy intensities and especially for countries that belong to the cold climate group. According to Fig. 14 the ergodic distribution is characterized by a single mode located around 0.4 for energy intensity and 0.7 for CO_2 emission intensity respectively. Probability mass shifts can be detected for the case of countries with temperate climate with the point to be 0.45 and 0.65 for the energy intensity variable and 0.7 and 1 for CO_2 emission intensity respectively.

6. Conclusions

Mitigating CO_2 emissions as well as the reduction of energy dependency and consumption have been regarded as a fundamental objective for European policy which in turn has promoted growing concerns and fueled burgeoning literature devoted towards the study of the convergence-divergence hypothesis. In the past, three decades empirical studies have implemented a variety of econometric methodologies, each one examining the existence of different types in investigating countries convergence in energy consumption and carbon emissions. To date, these empirical results have resulted in a number of effects.

In this paper, the convergence behavior of energy and CO_2 emissions variables and attributes across the EU-25 countries has investigated the application of the non-parametric methodology proposed by Quah (1993, 1996, 1997). However, the review of the literature provides a number of different approaches to the specific issue that each address substantially different aspects of convergence. In this work we used a non-parametric technique to study the dynamics of the entire distribution. The main reason for using the stochastic kernel is that it provides a complete picture of convergence behavior by using a multimodal distribution (Quah, 1993) while it allows for investigating the changes and the shape, for the examined variables.

Overall, our results support the hypothesis on non-convergence for all the examined variables across the European countries sample from 1970 to 2010. There are furthermore significant differences, between the examined variables with the formation of the corresponding clubs revealing a very limited degree of intra-distribution mobility. It seems that the examined countries tended to remain in

[10] The convergence process is also likely to changes in domestic energy mix or other explanatory factors. The examination of other factors, to the best of our knowledge,can not be achieved on the basis of this methodological framework. Thanks to a anonymous referee for this suggestion.

[11] We would like to thank an anonymous referee for highlighting this issue.

[12] The first group contains Belgium, Cyprus, Denmark, France, Greece, Ireland, Italy, Malta, Netherlands, Spain and UK while the second one Austria, Bulgaria, Czech Republic, Finland, Germany, Hungary, Luxembourg, Norway, Poland, Romania, Slovakia and Sweden.

[13] The estimations concerning energy consumption and carbonization index don't differentiate comparing our starting sample. Thus, the corresponding stochastic kernels, contour plots and ergodic densities are not presented at this section for space reasons and are available upon request.

their relative group/position during the entire 1970–2010 period. Further categorization of EU countries on the basis of their climatic conditions reveals significant differences regarding polarization phenomena with respect to the variables of energy intensity, CO_2 emissions and its intensity.

Moreover, the differences of energy consumption and intensity have been ascribed in several factors that vary from productive characteristics and structure of the economy to technological change. The above-mentioned can be facilitated by many processes of the economy including institutional setting, various economic indicators like volume of trade, absorptive capacity and learning ability to transfer and accumulate knowledge, the specific market conditions of each as well as their energy efficiency efforts. Finally, our findings concerning the specific variables reveal the presence of the decoupling effect across the sample countries throughout the period examined.

The information yielded in the CO_2 emissions and its intensity case reveals the significant role of fuel mix and its distribution for each country. Furthermore, it is related with general factors as different national policies, level of technology, the ambiguity of the role of internationalization and lax regulation. In addition, the formation of different clubs regarding the carbonization index indicates that uncoupling between emissions and energy consumption is present and depicts structural shifts for the national economy among sectors of greater to lower energy intensiveness.

Finally the results of ergodic distributions indicate a more optimistic picture for the case of energy consumption, CO_2 emissions and carbonization index. However, once the economic size of each country has been taken into account the results support the formation of bimodal distributions in indicating the existence of higher, energy and CO_2 intensity in the future. The present open up a debate on scheduling and implementing new energy and environmental policies for each European country.

Our analysis provides a non-parametric enhanced with stochastic characteristic methodology to study the dynamics of the entire distribution concerning energy consumption, CO_2 emissions releases, carbonization index and energy and CO_2 intensities. In addition, we provide empirical evidence on the shape and changes in the dynamics of the above-mentioned distributions. However, our framework suffers from some limitations. First, due to estimation idiosyncrasies further analysis is necessary to understand why the examined distributions evolves as it does. Second, we may have accounted for convergence or divergence over time but the introduction to the analysis of remaining components of convergence would be an additional future methodological first and empirical direction. Finally, it would be interesting to repeat this exercise employing a more diverse dataset not only in terms of countries but also in terms of time coverage.

Acknowledgments

I would like to thank Professor Tsekouras Kostas for constructive comments and invaluable advice in the preparation of this article and the Editor and two anonymous referees of this Journal for useful comments and suggestions that led to a substantial improvement of the paper. I would also like to express our gratitude to Professor Stefano Magrini for using its codes and Ioannou Roula for her help.

Appendix A

Table 1
Descriptive statistics of the used variables per country.

Country list					
Country name	Energy consumption	CO_2 emissions	Energy intensity	CO_2 emissions intensity	Carbonization index
Austria	2600.4 (47693.5)	54466.25 (8388.35)	0.131 (0.015)	0.281 (0.048)	2.121 (0.179)
Belgium	50573.84 (6600.76)	107773.33 (8308.43)	0.207 (0.031)	0.459 (0.136)	2.170 (0.319)
Bulgaria	27150.56 (2428.19)	55910.65 (9748.96)	0.471 (0.144)	1.144 (0.405)	2.401 (0.174)
Cyprus	1479.46 (686.32)	4734.95 (2770.94)	0.152 (0.025)	0.572 (0.746)	3.771 (4.955)
Czech Rep.	45095.32 (3044.22)	142796.13 (23808.33)	0.282 (0.052)	0.909 (0.265)	3.151 (0.386)
Denmark	18967.23 (1076.395)	55137.36 (5271.29)	0.148 (0.035)	0.434 (0.122)	2.901 (0.203)
Finland	28199.45 (5860.18)	51524.26 (7000.45)	0.256 (0.026)	0.485 (0.106)	1.874 (0.234)
France	220195.63 (36645.11)	379257.71 (39869.17)	0.161 (0.016)	0.297 (0.108)	1.800 (0.475)
Germany	338290.71 (14972.95)	922027.12 (102619.14)	0.178 (0.043)	0.498 (0.173)	2.721 (0.298)
Greece	20589.11 (6895.36)	63247.09 (22174.61)	0.103 (0.014)	0.321 (0.055)	3.082 (0.122)
Hungary	26081.72 (2920.16)	62318.12 (9480.08)	0.214 (0.035)	0.521 (0.138)	2.394 (0.289)
Ireland	104.82 (3002.55)	32083.65 (7864.43)	0.154 (0.044)	0.488 (0.164)	3.124 (0.182)
Italy	146708.64 (23314.23)	373655.32 (43724.96)	0.116 (0.013)	0.301 (0.046)	2.573 (0.132)
Luxembourg	3640.39 (507.81)	8117.01 (1588.32)	0.251 (0.131)	0.542 (0.261)	2.224 (0.201)
Malta	576.69 (243.48)	2327.05 (3548.97)	0.123 (0.029)	0.449 (0.371)	3.784 (0.980)
Netherlands	67683.18 (8372.26)	160428.61 (14888.84)	0.174 (0.033)	0.416 (0.091)	2.382 (0.112)
Norway	21713.37 (5078.58)	29929.15 (5786.19)	0.152 (0.021)	0.217 (0.046)	1.409 (0.120)
Poland	104708.88 (14347.55)	351838.12 (60395.82)	0.294 (0.093)	0.997 (0.347)	3.345 (0.151)
Romania	50039.73 (11943.09)	127064.91 (37390.44)	0.323 (0.088)	0.817 (0.255)	2.488 (0.181)
Slovakia	18324.25 (1801.16)	42485.72 (7610.67)	0.288 (0.058)	0.686 (0.207)	2.333 (0.338)
Spain	92014.84 (31737.66)	217096.31 (66670.51)	0.114 (0.006)	0.276 (0.024)	2.240 (0.171)
Sweden	46106.01 (4942.29)	57070.33 (14640.01)	0.223 (0.033)	0.298 (0.145)	1.285 (0.477)
UK	209465.41 (10344.22)	555529.61 (34915.08)	0.161 (0.041)	0.435 (0.141)	2.651 (0.205)

Note: Numbers indicate the mean value while parentheses correspond to the standard deviation.

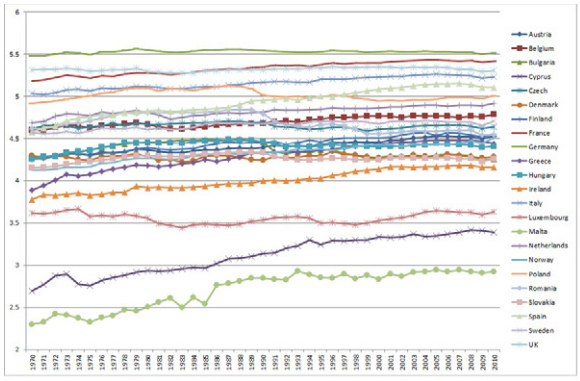
Table 2
Estimated results for β-convergence (linear least squares).

Explanatory variable	Coefficient	*t*-Statistic	Prob.
Energy consumption			
a	0.8112	14.325	0.000
β	−0.0213	-8.678	0.000
Weighted statistics			
R-squared	0.3304	Adjusted *R*-squared	0.3238
Half-life	42.179	Durbin-Watson stat	2.119
CO_2 emissions			
a	0.0032	4.325	0.000
β	−0.0184	−3.987	0.000
Weighted statistics			
R-squared	0.2897	Adjusted *R*-squared	0.2594
Half-life	44.985	Durbin-Watson stat	2.587
Carbonization index			
a	0.0102	3.375	0.0028
β	−0.0198	−2.241	0.009
Weighted statistics			
R-squared	0.3025	Adjusted *R*-squared	0.2857
Half-life	46.685	Durbin-Watson stat	2.987
Energy intensity			
a	0.0035	7.0325	0.000
β	−0.0225	−4.325	0.000
Weighted statistics			
R-squared	0.3697	Adjusted *R*-squared	0.3054
Half-life	44.258	Durbin-Watson stat	2.587
CO_2 intensity			
a	0.002	6.9125	0.000
β	−0.0185	−3.987	0.000
Weighted statistics			
R-squared	0.2698	Adjusted *R*-squared	0.2137
Half-life	41.258	Durbin-Watson stat	2.653

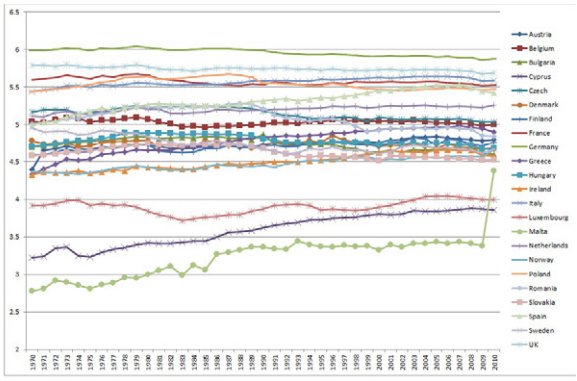
Table 3
Estimated results for σ-convergence.

Explanatory variable	Standard deviation		Variation coefficient		T_3 test.	
	1970	2010	1970	2010	Statistic	*p*-Value
Energy consumption	0.2784	0.2550	−7.6177	−8.2079	2.85	0.0094
	1970	2011	1970	2011		
CO_2 emissions	0.3153	0.2895	−3.6184	−3.7724	3.08	0.0039
	1970	2011	1970	2011		
Carbonization index	0.5742	0.5227	−5.1684	−5.2389	3.12	0.0032
	1970	2011	1970	2011		
Energy intensity	0.2783	0.2595	−2.9184	−2.1424	5.28	0.0000
	1970	2011	1970	2011		
CO_2 intensity	0.2153	0.1895	−2.6184	−1.9284	6.01	0.0000

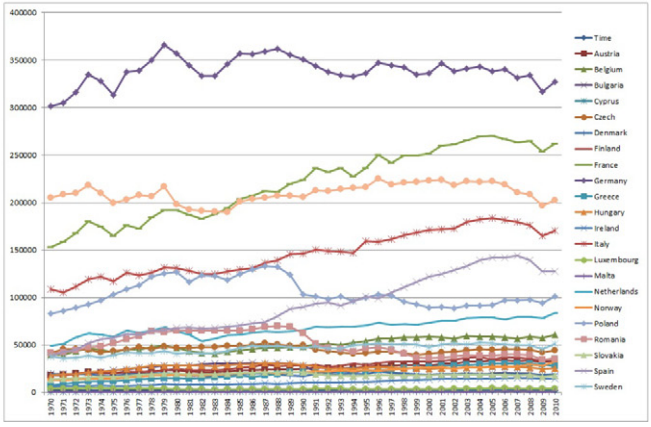
Note:The null hypothesis examine no converge. T_2 and T_3 statistics consider asymptotically distributed as a $\chi^2(1)$ and $N(0,1)$ respectively. Results are the same for T_2 statistic for all the examined variables.



(a) Energy consumption



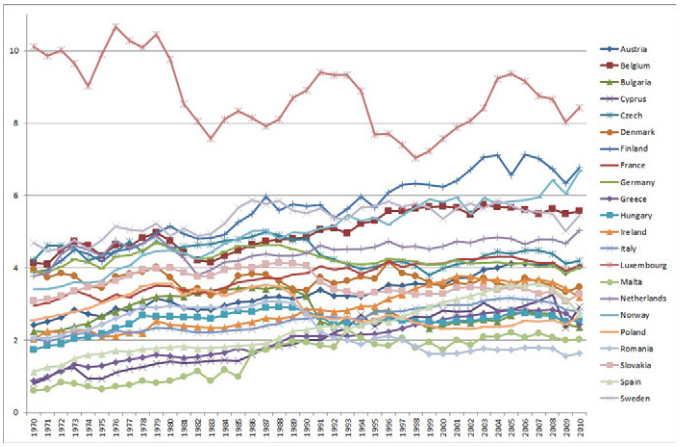
(b) CO_2 emissions



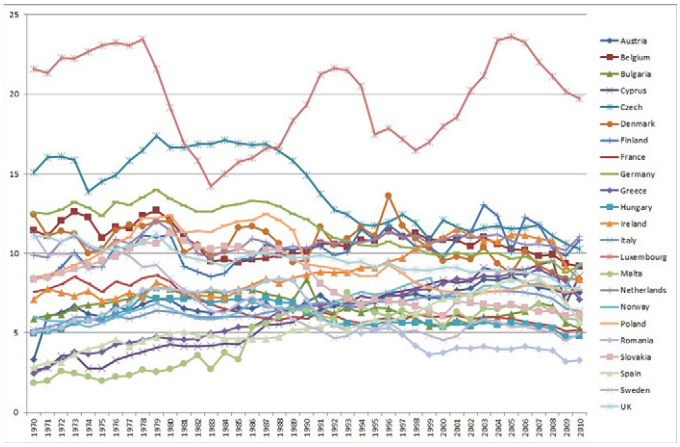
(c) Carbonization index

Fig. 1. Transition paths for energy consumption, CO_2 emissions releases and carbonization index.

Appendix B



(a) Energy intensity



(b) CO_2 emissions intensity

Fig. 2. Energy and CO_2 intensities evolution.

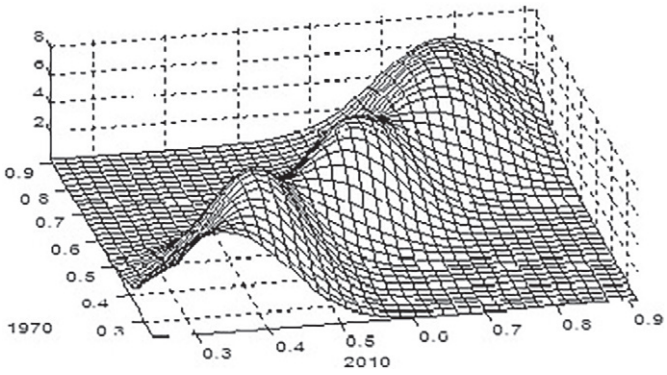


Fig. 3. Stochastic Kernel of the distribution of energy consumption per capita.

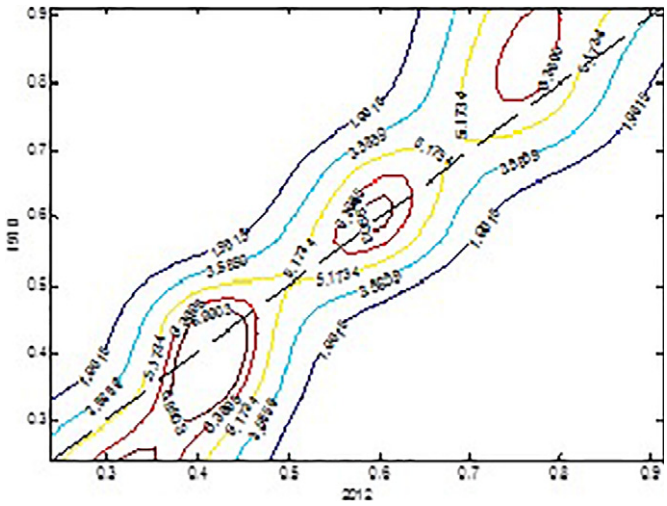


Fig. 4. Contour plot of the distribution of energy consumption per capita.

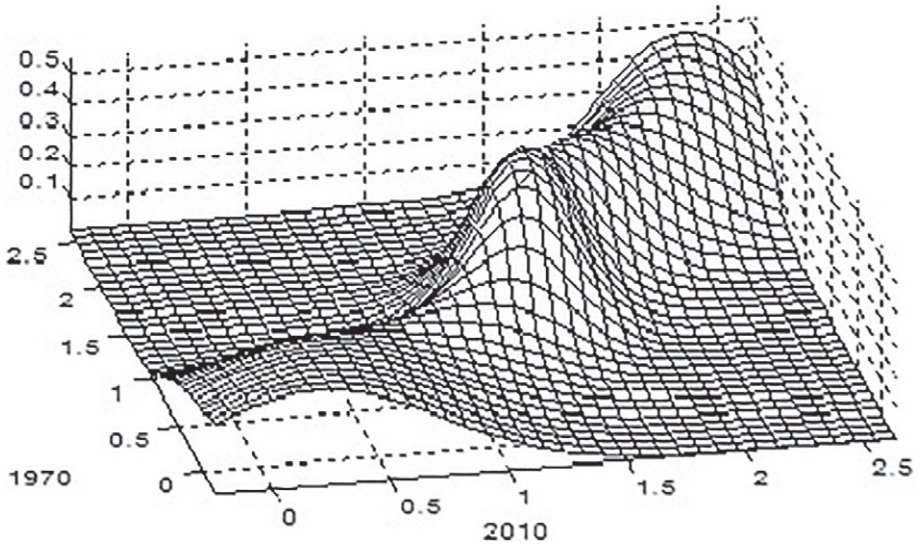


Fig. 5. Stochastic Kernel of the distribution of energy intensity distribution.

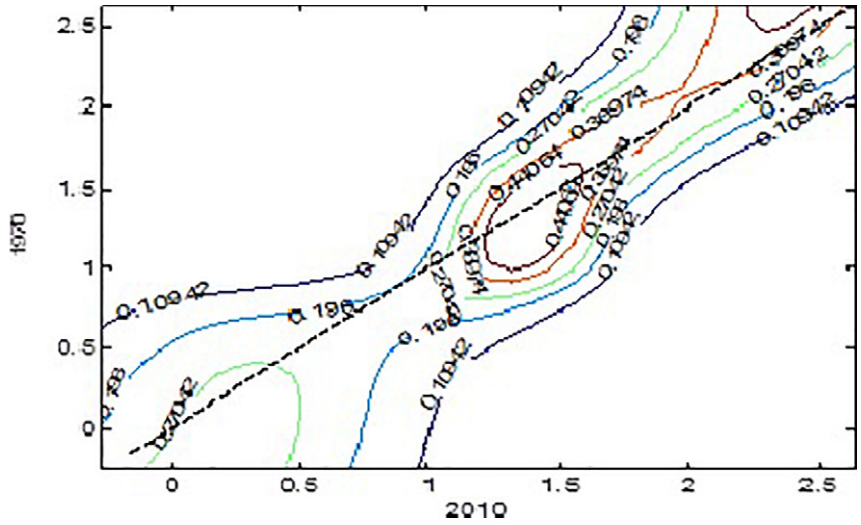
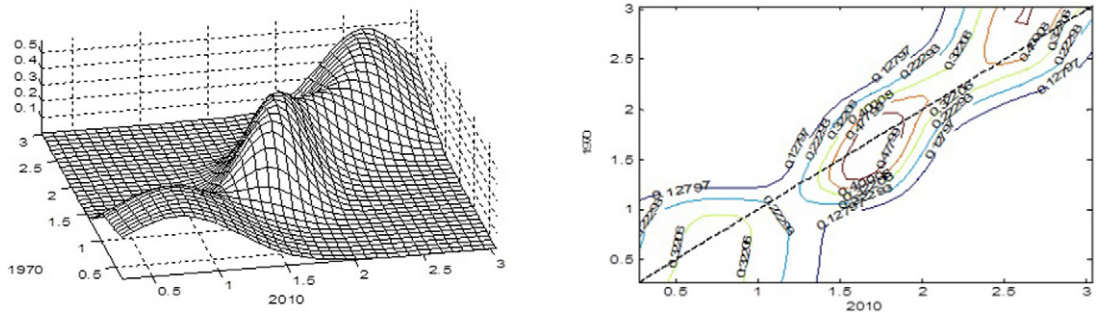
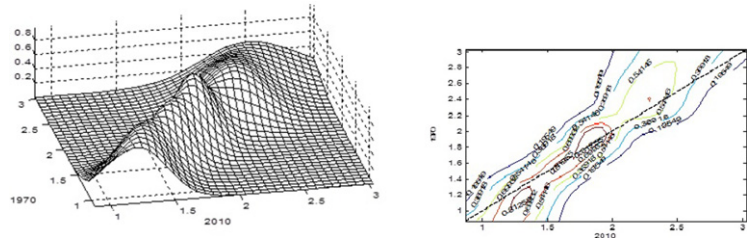


Fig. 6. Contour plot of the distribution of energy intensity distribution.



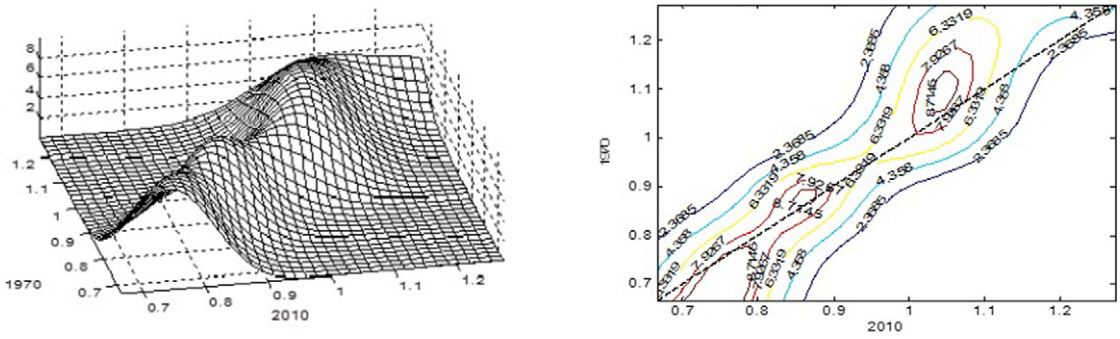
(a) Stochastic Kernel (b) Contour plot

Fig. 7. Stochastic Kernel and contour plot of the distributions of CO_2 emissions per capita.



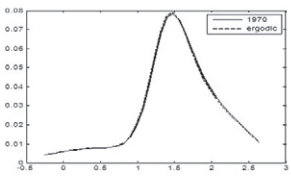
(a) Stochastic Kernel (b) Contour plot

Fig. 8. Stochastic Kernel and contour plot of CO_2 intensity.

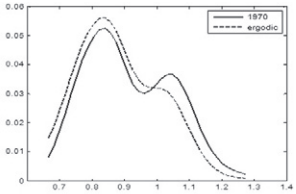


(a) Stochastic Kernel (b) Contour plot

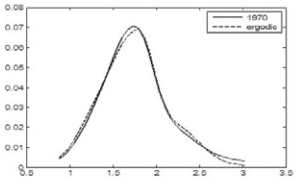
Fig. 9. Stochastic Kernel and contour plot of Carbonization Index.



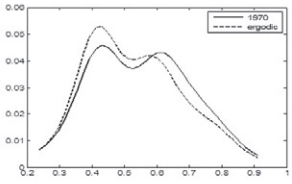
(a) Energy consumption per capita



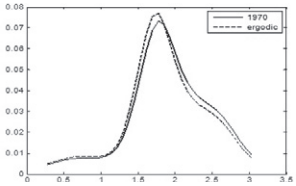
(b) Energy intensity



(c) CO_2 emissions

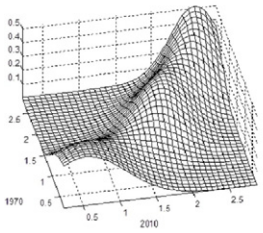


(d) CO_2 emission intensity

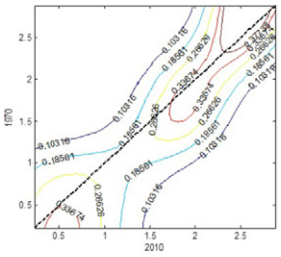


(e) Carbonization index

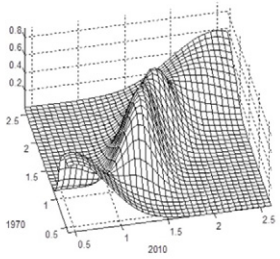
Fig. 10. Ergodic densities for the examined variables.



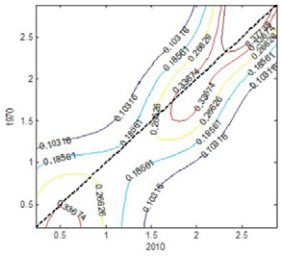
(a) Stochastic Kernel-temperate



(b) Contour plot-temperate

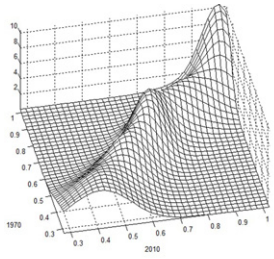


(c) Stochastic Kernel-cold

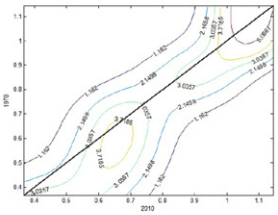


(d) Contour plot-cold

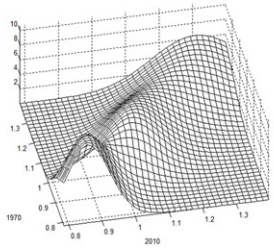
Fig. 11. Stochastic Kernel and contour plot for CO_2 emissions climate groups.



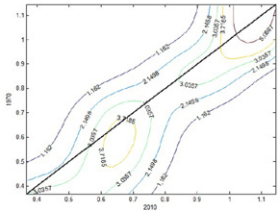
(a) Stochastic Kernel-temperate



(b) Contour plot-temperate

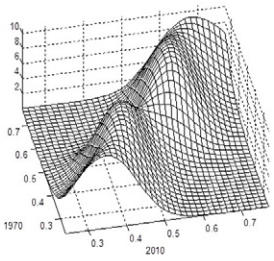


(c) Stochastic Kernel-cold

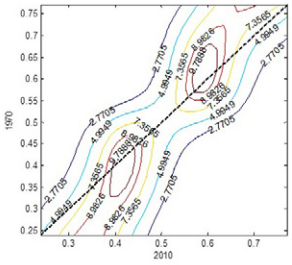


(d) Contour plot-cold

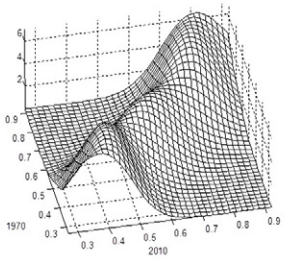
Fig. 12. Stochastic Kernel and contour plot for CO_2 emission intensity climate groups.



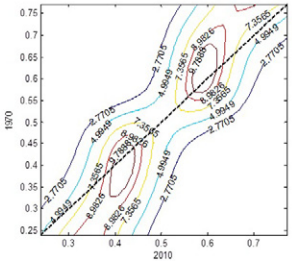
(a) Stochastic Kernel-temperate



(b) Contour plot-temperate

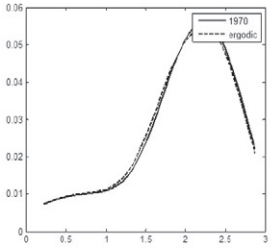


(c) Stochastic Kernel-cold

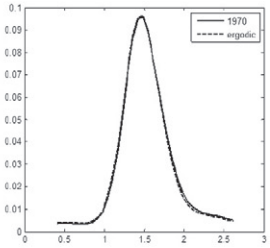


(d) Contour plot-cold

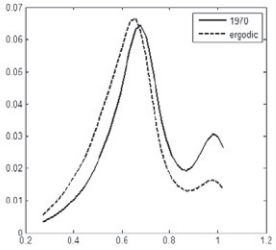
Fig. 13. Stochastic Kernel and contour plot for energy intensity climate groups.



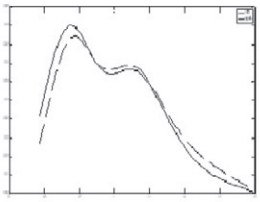
(a) Ergodic density-temperate



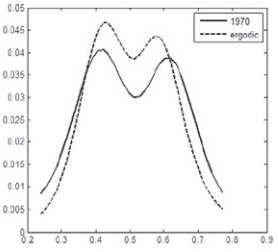
(b) Ergodic density-cold



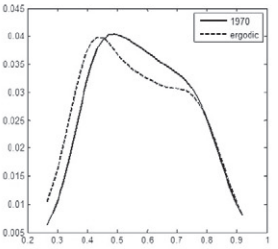
(c) Ergodic density-temperate



(d) Ergodic density-cold



(e) Ergodic density-temperate



(f) Ergodic density-cold

Fig. 14. Ergodic densities for CO_2 emissions, CO_2 emission and Energy Intesities climate groups.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2017.11.015.

References

Aldy, J., 2006. Per capita carbon dioxide emissions: convergence or divergence? Environ. Res. Econ. 33 (4), 533–555.

Andrade, E., Laurini, M., Madalozzo, R., Pereira, P.L.V., 2004. Convergence clubs among Brazilian municipalities. Econ. Lett. 83 (2), 179–184.

Antonelli, C., 2006. Localized technological change and factor markets: Constraints and inducements to innovation. Struct. Chang. Econ. Dyn. 17 (2), 224–247.

Barassi, M.R., Cole, A.M., Elliott, J.R.R., 2008. Stochastic divergence or convergence of per capita carbon dioxide emissions: re-examining the evidence. Environ. Res. Econ. 40 (1), 121–137.

Barro, R., Sala-i-Martin, X., 1991. Convergence across states and regions. Brook. Pap. Econ. Act. 1990 (1), 107–182.

Barro, R., Sala-i-Martin, X., 1992. Convergence. J. Polit. Econ. 100 (2), 223–251.

Baumol, W.J., 1986. Productivity Growth,Convergence and welfare: What the Long-Run data show. Am. Econ. Rev. 76 (5), 1072–1085.

Bimonte, S., 2009. Growth and environmental quality: testing the double convergence hypothesis. Ecol. Econ. 68 (8), 2406–2411.

Binswanger, H.P., Ruttan, V.W., Ben-Zion, U., Janvry, A.D., Evenson, R., 1978. Induced Innovation; Technology, Institutions, And Development.

Bulli, S., 2001. Distribution dynamics and cross-country convergence: a new approach. Scott. J. Polit. Econ. 48, 226–243.

Camarero, M., Picazo-Tadeo, A.J., Tamarit, C., 2013. Are the determinants of CO2 emissions converging among OECD countries. Econ. Lett. 118 (1), 159–162.

Carlino, G.A., Mills, L.O., 1993. Are US regional incomes converging?: a time series analysis. J. Monet. Econ. 32 (2), 335–346.

Carree, M., Klomp, L., 1997. Testing the convergence hypothesis: a comment. Rev. Econ. Stat. 79 (4), 683–686.

Costantini, V., Crespi, F., Palma, A., 2017. Characterizing the policy mix and its impact on eco-innovation: A patent analysis of energy-efficient technologies. Res. Policy 46 (4), 799–819.

Costantini, V., Gracceva, F., Markandya, A., Vicini, G., 2007. Security of energy supply: comparing scenarios from a European perspective. Energy Policy 35 (1), 210–226.

Del Río González, P., 2009. Interactions between climate and energy policies: the case of Spain. Clim. Pol. 9, 119–138.

Durlauf, S.N., Johnson, P.A., Temple, J.R., 2005. Growth econometrics. Handb. Econ. Growth 1, 555–677.

Durlauf, S.N., Quah, D., 1999. The New Empirics of Economic Growth. In: Taylor, J.B., Woodford, M. (Eds.), Handbook of Macroeconomics. vol. (1.A). North Holland Elsevier Science, Amsterdam.

Easterly, W., Levine, R., 2001. What have we learned from a decade of empirical research on growth? It's Not Factor Accumulation:Stylized Facts and Growth Models. World Bank Econ. Rev. 15 (2), 177–219.

European Commission, 2013. Communication from the Commission to the European Parliamnet and the Council: Implementing the Energy Efficiency Directive - Commission Guidance.

European Commission, 2007. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on Energy Efficiency, Amending Directives 2009/125/EC and 2010/30/EU and Repealing Directives 2004/8/EC and 2006/32/EC.

Ezcurra, R., 2007a. Is there cross-country convergence in carbon dioxide emissions? Energy Policy 35 (2), 1363–1372.

Ezcurra, R., 2007b. Distribution dynamics of energy intensities: a cross-country analysis. Energy Policy 35 (10), 5254–5259.

Fingleton, B., 1999. Estimates of time to economic convergence: an analysis of regions of the european union. Int. Reg. Sci. Rev. 22 (1), 5–34.

Fingleton, B., McCombie, J.S., 1998. Increasing returns and economic growth: some evidence for manufacturing from the European Union regions. Oxf. Econ. Pap. 50 (1), 89–105.

Fotopoulos, G., 2006. Onparametric analysis of regional income dynamics: the case of Greece. Econ. Lett 91, 450–457.

Furceri, D., 2005. And -convergence: A mathematical relation of causality. Econ. Lett. 89 (2), 212–215.

Goldemberg, J., 1996. A note on energy intensity of developing countries. Energ. Policy 24, 759–761.

Herrerias, M.J., 2012. CO2 weighted convergence across the EU-25 countries (1920-2007). Appl. Energy 92, 9–16.

Hoppmann, J., Peters, M., Schneider, M., Hoffmann, V., 2013. The two faces of market supportHow deployment policies affect technological exploration and exploitation in the solar photovoltaic industry. Res. Policy 42, 989–1003.

IEA, 2000. (International Energy Agency)/{OECD}(Organisation for Economic Cooperation and Development) (2000): Experience Curves for Energy Technology Policy, Paris.

IEA, 2008. World Energy Outlook 2008. Available from: http://www.worldenergyoutlook.org/.

Climate Change, I.P.C.C., 2007. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. In: Pachauri, R.K., Reisinger, A. (Eds.), Synthesis Report. Core Writing Team. IPCC, Geneva, Switzerland.

Jakob, M., Haller, M., Marschinski, R., 2012. Will history repeat itself? Economic convergence and convergence in energy use patterns. Energy Econ. 34 (1), 95–104.

Jobert, T., Karanfil, F., Tykhonenko, A., 2010. Convergence of per capita carbon dioxide emissions in the EU: Legend or reality? Energy Econ. 32 (6), 136–1373.

Jenkins, J.D., 2014. Political economy constraints on carbon pricing policies: What are the implications for economic efficiency, environmental efficacy and climate policy design? Energy Policy 69, 467–477.

Johnson, A.P., 2000. A nonparametric analysis of income convergence across the US States. Econ. Lett. 69, 219–223.

Johnson, A.P., 2005. A continuous state space approach to "Convergence by Parts. Econ. Lett. 86 (3), 317–321.

Le Pen, Y., Sévi, B., 2010. On the non-convergence of energy intensities: evidence from a pair-wise econometric approach. Ecol. Econ. 69 (3), 641–650.

Lee, C.C., Chang, C.P., 2008. New evidence on the convergence of per capita carbon dioxide emissions from panel seemingly unrelated regressions augmented Dickey-Fuller tests. Energy 33 (9), 1468–1475.

Liddle, B., 2009. Electricity intensity convergence in IEA/OECD countries: Aggregate and sectoral analysis. Energy Policy 37 (4), 1470–1478.

Liddle, B., 2010. Revisiting world energy intensity convergence for regional differences. Appl. Energy 87 (10), 3218–3225.

Magrini, S., 1999. The evolution of income disparities among the regions of the european union. Reg. Sci. Urban Econ. 29 (2), 257–281.

Magrini, S., 2004. Regional (Di)Convergence. In: Henderson, J.V., Thisse, J.F. (Eds.), Handbook of Regional and Urban Economics. vol. 4. Elsevier, Amsterdam.

Mankiw, N.G., Romer, D., Weil, D.N., 1992. A contribution to the empirics of economic growth. Q. J. Econ. 107 (2), 407–437.

Markandya, A., Pedroso-Galinato, S., Streimikiene, D., 2006. Energy intensity in transition economies: Is there convergence towards the EU average? Energy Econ. 28, 121–145.

Marrero, G.A., 2010. Greenhouse gases emissions, growth and the energy mix in Europe. Energy Econ. 32 (6), 1356–1363.

Meyn, S.D., Tweedie, R.L., 1996. Markov Chains Annd Stochastic Stability. Springer-Verlang, Berlin.

Mielnik, O., Goldemberg, J., 2000. Converging to a common pattern of energy use in developing and industrialized countries. Energy Policy 28, 503–508.

Miketa, A., Mulder, P., 2005. Energy productivity across developed and developing countries in 10 manufacturing sectors: patterns of growth and convergence. Energy Econ. 27, 429–453.

Mulder, P., De Groot, L.F.H., 2007. Sectoral energy and labour productivity convergence. Environ. Res. Econ. 36, 85–112.

Mulder, P., De Groot, L.F.H., 2012. Structural change and convergence of energy intensity across OECD countries, 1970-2005. Energ. Econ. 34, 1910–1921.

Nguyen Van, P., 2005. Distribution dynamics of CO2 emissions. Environ. Res. Econ. 32 (4), 495–508.

Nielsson, L., 1993. Energy intensity in 31 industrial and developing countries 1950-88. Energy 18, 309–322.

Nordhaus, W.D., 2007. Alternative measures of output in global economic-environmental models: Purchancing power parity or market exchange rates? Energy Econ. 29 (3), 349–372.

Padilla, E., Duro, J.A., 2011. Inequality across countries in energy intensities: an analysis of the role of energy transformation and final energy consumption. Energy Econ. 33 (3), 474–479.

Padilla, E., Duro, J.A., 2013. Explanatory factors of CO2 per capita emission inequality in the European Union. Energy Policy 62, 1320–1328.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of the Köppen-Geiger climate classification. Hydrol. Earth Syst. Sci. Discuss. 4 (2), 439–473.

Pesaran, M., 2007. A pair-wise approach to testing for output and growth convergence. J. Econ. 138, 312–335.

Quah, D.T., 1993. Galton's Fallacy and the Convergence Hypothesis. Scand. J. Econ. 95, 427–443.

Quah, D.T., 1996. Convergence empirics across economies with (some) capital mobility. J. Econ. Growth 1, 95–124.

Quah, D.T., 1997. Empirics for Growth and Distribution: Stratification, Polarization, and Convergence Clubs. J. Econ. Growth 2, 27–59.

Regnier, E., 2007. Oil and energy price volatility. Energy Econ. 29 (3), 405–427.

Reichardt, K., Rogge, K., 2016. How the policy mix impacts innovation: findings from company case studies on offshore wind in Germany. Environ. Innov. Soc. Trans. 18, 62–81.

Romero-Ávila, D., 2008. Convergence in carbon dioxide emissions among industrialised countries revisited. Energy Econ. 30, 2265–2282.

Solow, R.M., 1956. A contribution to the theory of economic growth. Q. J. Econ. LXX 65–94.

Solow, R.M., 1957. Technological change and the aggregate production function. Rev. Econ. Stat. XXXIX 312–320.

Soytas, U., Sari, J., 2009. Energy consumption, economic growth, and carbon emissions: Challenges faced by an EU candidate member. Ecol. Econ. 68 (6), 1667–1675.

Stegman, A., 2005. Convergence in carbon emissions per capita. CAMA Working Paper Series. (8/2005).

Strazicich, C.M., List, J.A., 2003. Are CO2 emission levels converging among industrial countries? Environ. Res. Econ. 24, 263–271.

Vogel, D., 1995. Trading up Consumer and Environmental Regulation in the Global Economy. Harvard University Press, Cambridge.

Westerlund, J., Basher, S., 2008. Testing for convergence in carbon dioxide emissions using a century of panel data. Environ. Res. Econ 40, 109–120.